Engineering Statics in High School Physics Courses

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INTRODUCTION

Physics teachers have a number of goals for their students: to learn scientific concepts and apply them, to become excited about science, and to recognize the relevance of science to the practical world. This paper describes an instructional approach inspired by engineering education that promotes these goals.

Many engineers, in particular mechanical and civil engineers, apply Newtonian mechanics in their professional activities. Typically, engineering students first see the applications of Newton's laws in engineering mechanics courses of Statics and Dynamics after they have taken an introductory physics course. While physics textbooks have chapters on rotational motion of a finite body and equilibrium accounting for rotation, these topics rarely receive significant attention in physics courses. Engineering statics focuses on equilibrium of finite bodies, accounting for the balance of both rotational and translational tendencies. This topic coverage enables students to study a far richer – and practically relevant - set of physical situations than when they are confined to equilibrium of particles for which only translation motion is at issue.

Given our opportunities to see Newtonian mechanics applied in diverse circumstances, teachers of engineering mechanics are able to offer physics teachers new ways to excite their students about science. As one teacher of engineering mechanics, I argue that blending engineering statics topics into physics courses offers new opportunities to make physics concepts more tangible to students and to excite students about STEM more generally. Because so much of our everyday experience in the real world can be explained with engineering statics, it helps students see that science education is indeed highly relevant. While one can find articles for physics teachers on individual statics problems [1, 2], there has not been a widespread movement to incorporate more statics into physics as proposed here, although the lost opportunity has been lamented in some quarters [3].

CONCEPTUAL TRADEOFF IN LEARNING ENGINEERING STATICS

There is a trade-off in the conceptual challenges of learning statics of finite bodies versus the dynamics of particles. In one sense, statics is simpler than dynamics. While the distinction between constant velocity and acceleration is important, students are not burdened with quantifying accelerations or velocities, provided the body is not moving or the velocity is clearly constant. On the other hand, statics is more complex: students do need to learn about tendencies of forces to impart rotations, even though the rotational acceleration need not be quantified.

ENGINEERING STATICS IDEAS LESS FAMILIAR TO PHYSICS TEACHERS

Engineering statics requires a few ideas that may be unfamiliar to some physics teachers.

More Representative Depictions of Isolated Systems

In physics, it is customary to represent a body being isolated in a free body diagram as a point from which force vectors emanate. While the point particle model works well in many situations in physics, bodies that are subject to rotation must be considered as having finite size. The forces acting on them can act through various points, not just through the "center". Hence students must learn to draw the body in the free body diagram with finite size and with sufficient detail that the placement of forces can be represented. For example, in the case of a block on an inclined plane, it is clearly necessary to draw a block rather than a dot if the propensity to tip over is to be investigated. In fact, it might be more natural for students to represent forces in this way, and the resulting free body diagrams may be more obviously representative of the modeled situation.

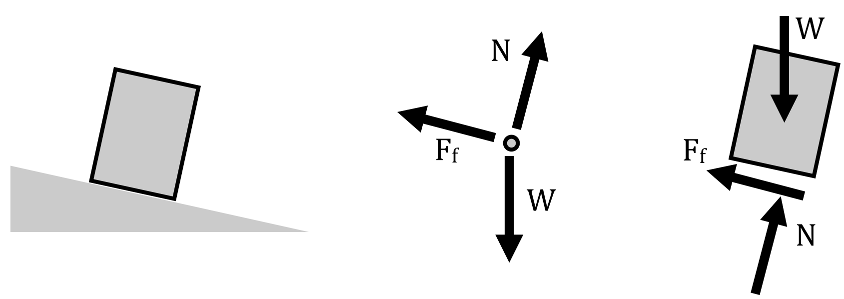

Figure 1. Different representations for bodies and forces common in physics versus engineering statics

Because engineered artifacts can involve multiple connected parts, students must learn to be clear when drawing free body diagrams exactly which parts are represented in the diagram. Drawing bodies as other than dots can help to distinguish parts. Further, when drawing a force vector in a free body diagram, students should have clearly in mind which body exerts the force. In my experience, student uncertainty on, or lack of attention to, what body or bodies make up the system and what body exerts a given force causes many errors in Newtonian mechanics. These and other conceptual challenges that students face in statics, and their relation to conceptual challenges faced in physics, have been documented and analyzed [4].

Concepts Related to Rotation

In engineering we not only need to produce more elaborate free body diagrams, we also need to address interactions that are relevant to rotations more comprehensively than is typically done in physics. In particular, we need to distinguish two concepts, the moment and the couple, which in physics are usually subsumed under the single term torque. The moment about a point due to a force describes the force's tendency to cause rotation and is expressed in vector form as **r** x **F**. For a body in equilibrium, the total moment of all forces is zero. To find relations between forces that maintain equilibrium we can consider the sum of moments about any point. For two bodies contacting at a point, the real physical interaction is represented by the equal and opposite forces that the two bodies exert on each other. The moment due a force about a point represents a hypothetical tendency of that force to cause rotation of the body it acts on if the body were somehow pierced by an axis at the point and free to spin about it. A study of student understanding of equilibrium of a balance beam [5] certainly suggests that the rotational effects of forces are not easy for many students to learn.

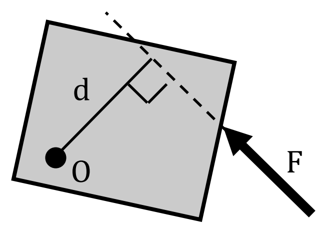

Figure 2. Moment due to force F about the point O depends on the perpendicular distance d: $M|_O = Fd$

The couple is a related and useful concept in engineering statics; it describes, for example, the interaction between my hand and the screwdriver I am trying to turn. There is actually a complex distribution of forces between my hand and the screwdriver, a distribution that is difficult to know in detail. But, the net effect of my hand is to exert no net tendency to translate, but a net tendency to rotate the screwdriver about its axis. This is an interaction that cannot be represented by a single force, which would give a tendency to translate. It would be arbitrary to represent this interaction with two forces or any particular number of forces. In engineering statics we refer to this interaction as a couple, or sometimes (very unfortunately too often) as a moment. We represent this interaction in two dimensions with a curved arrow as opposed to a straight arrow representing a force. It points in the direction of the exerted turning and its magnitude is the net moment exerted. Newton's 3rd Law applies to this situation also: interacting bodies exert equal and opposite couples on each other. When the interaction involves a shaft, and the tendency to rotate is about the shaft axis, engineers often term this couple a torque (such as the torque a motor shaft exerts on the gear to which it is connected). Note that when referring to the moment due to a force about a point, we never draw the curved arrow. Arrows should represent physical interactions between objects – forces or couples - not their hypothetical tendencies to rotate or translate.

Figure 3. Photos and representation of a couple between hand and screwdriver

Modeling Interactions Between Bodies Connected in Various Ways

Applying Newton's laws to realistic engineered artifacts requires the modeling of various types of connections. Engineered artifacts often consist of multiple parts. Two parts can be connected so that the motion of each relative to the other is constrained. For example, two bodies connected by a pin connection (or pin joint) are capable of rotating with respect to each other about the pin axis, but cannot translate with respect to each other. There are connections that constrain relative motions in other ways as well.

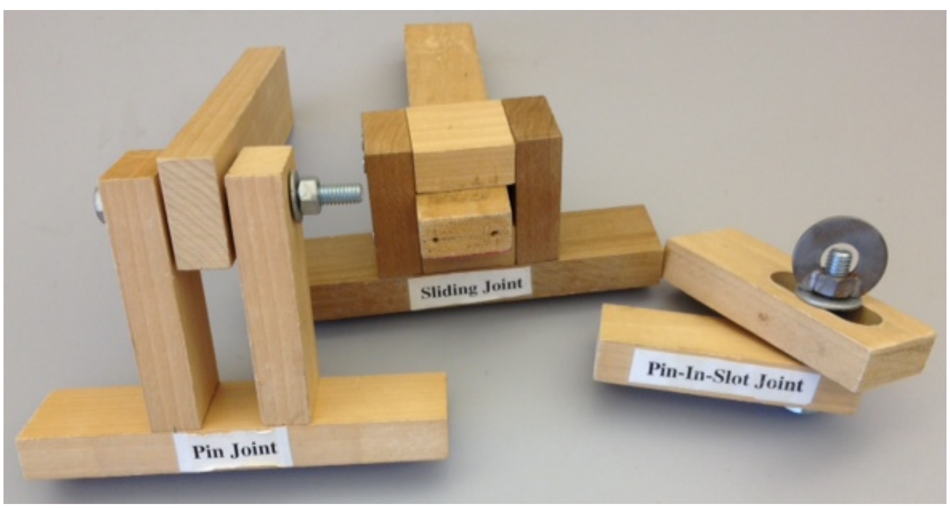

Figure 4. Wood-block models of connections between objects.

While the force direction is known for a cord attached to a body or two bodies in normal contact, the interaction at a connection may need to be represented by a force of unknown direction and magnitude, and also possibly by a couple. In statics we want students to learn to represent interactions properly at connections and to apply conditions of the equilibrium that relate them to other forces.

IMPLEMENTATION OF STATICS IN HIGH SCHOOLS

A casual perusal of engineering statics textbooks might lead one to view statics as beyond the capabilities of most high school students. Statics textbooks for engineering students, which took their modern form in the 1950s, have students learn three-dimensional vector algebra. While such a mathematical arsenal is needed for some problems, the core ideas and many problems of practical use can be solved with very simple algebra and elementary trigonometry. The unnecessary (in my view) mathematization of statics has been pointed out [6], along with the benefits of learning statics in the context of simple objects. This preference for physical objects versus mathematical formalism has had a strong impact on my own teaching of statics at the college level, and it is critical to making engineering statics accessible to high school physics students.

Because some statics concepts are largely unfamiliar to students (and teachers), and there is the potential for undue focus on mathematical analysis of equilibrium, it is highly beneficial to teach statics in high school with the aid of manipulatives. It is possible to engage physics students in the basic ideas of statics using simple, inexpensive artifacts that are readily assembled often from materials such as wood and Plexiglas. Furthermore, simple devices, such as a food scales, spring scales, and bathroom scales are sufficient to obtain measurements of relevant forces. A variety of such artifacts have been fabricated. High school physics teachers are using them in their physics classes in Pittsburgh area schools.

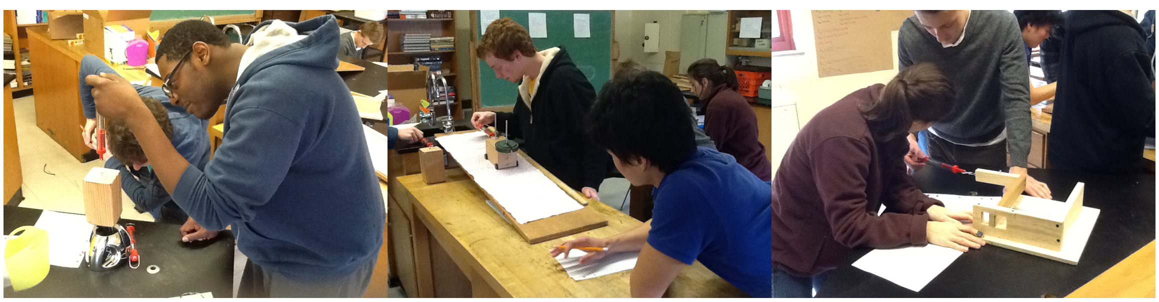

Figure 5. Students engaged in activities involving statics

We intend to post lesson plans on the web – these lesson plans are flexible, allowing different physics teachers to select and implement them at their own pace, interspersed within or placed after more traditional mechanics topics. A list of the items needed for various lessons is being developed as well as drawings so that schools can fabricate artifacts as needed. We also intend to run workshops that enable physics teachers to gain greater comfort in teaching students these ideas. The level of statics that can be treated in high schools also lends itself to further discussions of forces associated with positioning of the human body, simple robots that involve servomotors, and consumer products such as reacher-grabbers. Lessons involving these more advanced applications are also under development.

While it remains to be seen whether this idea will catch on broadly, the initial response from students has been extremely promising, as the following anecdotes convey. The activities have been tested out most extensively in a Pittsburgh city public school in an AP mechanics course. Student experience with the materials was sufficiently positive that the instructor has reformulated them for her first year physics class. At the same time, students in an AP mechanics/EM class, who were viewed as having too much in their physics course to allow for the new statics activities, heard what their peers in AP mechanics were doing. They prevailed upon this same highly energetic, capable teacher to have them also do the activities, without credit, during their once-a-week lunchtime study hall. Portions of these activities have been used for two successive years in a second year algebra-based physics class at independent school in the Pittsburgh area. On another front, planning has been under way in a Pittsburgh suburban public high school for a new, year-long physics elective in engineering statics, which will first be offered during the 2013-2014 academic year. It was originally hoped that at least 20 students would sign up for the first year. Instead, an unexpected 68 students signed up. This surprisingly positive response provides evidence of students' desire to take a class that allows them to apply physics principles to relevant, everyday experiences.

ACKNOWLEDGMENTS

I want to thank Janet Waldeck, Drew Haberberger, and Mark Skinner for their contributions to this paper and for helping to develop the materials and test them out in their high school physics classrooms. I am grateful to Ed Wojciechowski for his assistance in designing and fabricating many of the classroom artifacts.

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